The Robotic Lunar Exploration Program (RLEP) – An Introduction to the Goals, Approach, and Architecture

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The Vision for Space Exploration calls for undertaking lunar exploration activities to enable sustained human and robotic exploration of Mars and beyond, including more distant destinations in the solar system. In support of this vision, the Robotic Lunar Exploration Program (RLEP) is expected to execute a series of robotic missions to the Moon, starting in 2008, in order to pave the way for further human space exploration. This paper will give an introduction to the RLEP program office, its role and its goals, and the approach it is taking to executing the charter of the program. The paper will also discuss candidate architectures that are being studied as a framework for defining the RLEP missions and the context in which they will evolve.

I. Introduction

NASA's Vision for Space Exploration has the fundamental goal of advancing scientific, security and economic interests through a robust space exploration program. To help fulfill this vision, NASA has initiated a series of robotic missions to the Moon to prepare for and support future human and robotic exploration activities on the Moon, Mars, and beyond. The primary purpose of the lunar robotic preparation step is to reduce risk, enhance mission success, and reduce the cost of future human missions, as well as to enable the scientific activities human explorers will undertake on the Moon. These objectives will be accomplished by designing and implementing a program of robotic lunar missions to collect critical measurements, demonstrate key technologies, and emplace essential infrastructure, while also seeking to make discoveries about what the Moon can offer as a scientific stepping-stone to Mars and beyond. That program is the Robotic Lunar Exploration Program (RLEP).

The RLEP was initiated on February 11, 2004, in response to a memorandum received from the Associate Administrator for Space Science, which assigned management responsibility of the RLEP to the Goddard Space Flight Center (GSFC) and directed the establishment of a dedicated program office to manage this new activity. This action was taken in direct response to the President's Vision for U.S. Space Exploration (cf, "A Renewed Spirit of Discovery" policy statement) issued in January 2004 where NASA was directed to, "Starting no later than 2008, initiate a series of robotic missions to the Moon to prepare for and support future exploration activities." The charter of the RLEP was thereby rooted in the very foundation of the new Exploration Vision, as mandated by the current Administration.

II. Program Overview

The RLEP is expected to execute a series of robotic missions to the Moon, starting in 2008, in order to pave the way for human exploration missions to the Moon, and ultimately, to Mars and beyond. The role of the RLEP is to ensure that all lunar flight missions are integrated into a program in a manner that allows them to achieve mission success, and support the larger goal of integrated human and robotic exploration. For planning purposes, each mission is envisioned to be within the NASA Discovery-class scope (~$400M full cost, full lifecycle, including instruments, spacecraft, launch vehicle, ground systems, and mission operations – phases A-E inclusive), and to be developed in four years or less. While the first flight mission will be purely orbital, subsequent missions will undoubtedly include surface elements (landed, or impacted), as required to best provide the required measurements, validation of technologies, and risk mitigation for follow-on human missions. However, it is possible that each

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flight mission will include an orbital element, if for no other reason than to provide a platform for payload delivery and/or communications back to Earth.

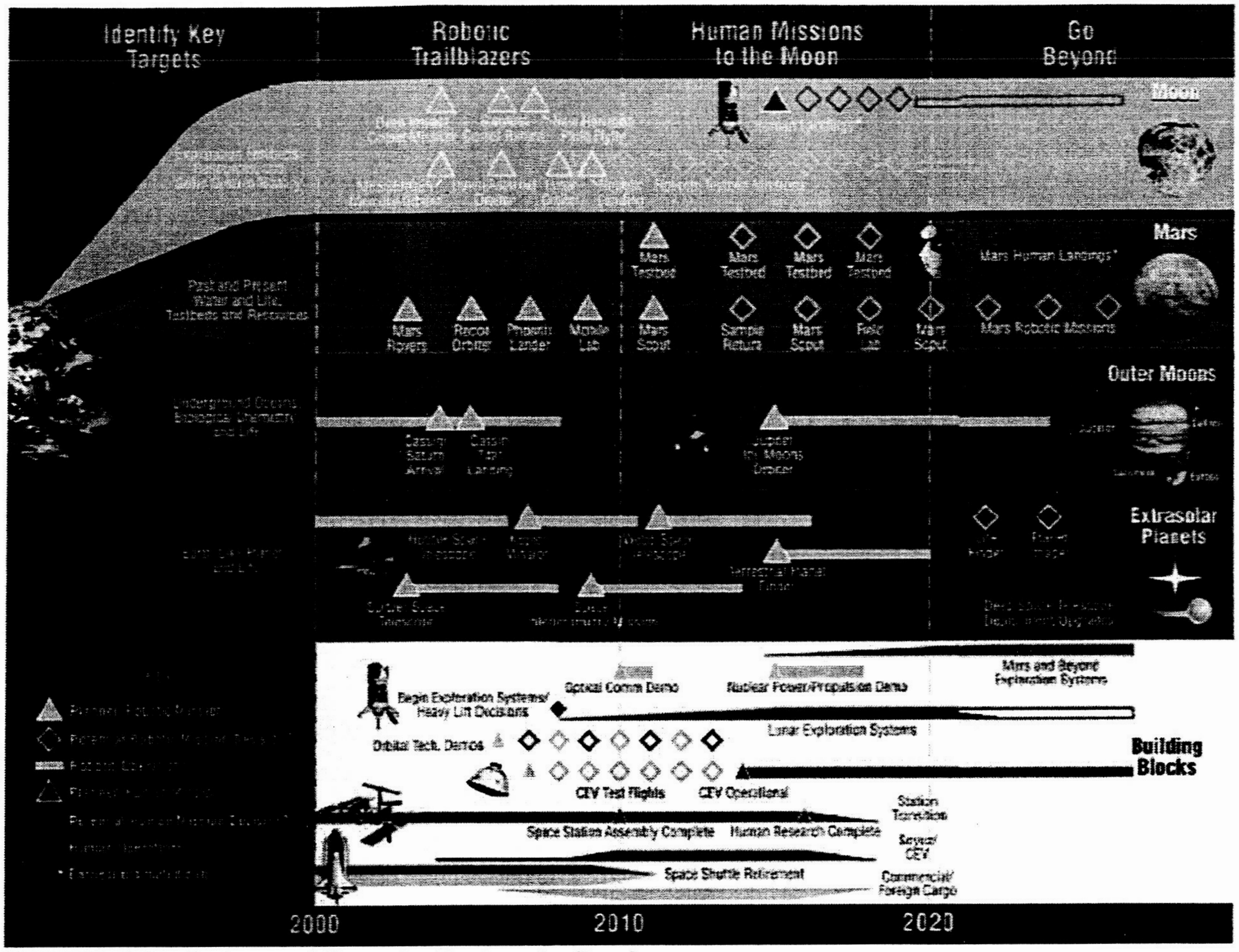

Figure 1. Solar System and Beyond – Exploration Roadmap

The RLEP embraces a broad range of mission content, ranging from quantitative remote sensing of the lunar surface, assessment of the lunar environment on human adaptation to space, prospecting for in-situ resources, supporting technology maturation for human-tended Exploration systems, to the emplacement of infrastructure for human in situ activities. The series of robotic mission will progress from precursor mission activities for extended duration operations, to long duration operations, and ultimately to a sustained presence on the Moon.

One goal of the RLEP is to provide an early assessment of candidate human exploration sites on the Moon, followed by a risk mitigation strategy for both the technology developments needed for human exploration and the emplacement of supporting infrastructure. This will require a comprehensive, quantitative assessment of the character of the lunar surface (and shallow subsurface) environment in all regions deemed relevant to human exploration activities. Although much is known from the Apollo missions (and their robotic predecessors), many factors still remain unanswered in terms of human health, safety, and performance, particularly for longer lunar surface stays and in association with the largely unexplored lunar polar regions, where the potential for discovering and then using accessible water/ice as a resource is a possibility. RLEP will provide observational data in the form of fully calibrated and validated measurements to help address these questions. It will also assist in meeting the challenges posed by human exploration technology maturation, as well as emplacement of the operations support infrastructure, both Moon- and Earth-based. RLEP will provide critical elements in support of all phases of the planned human exploration program for the Moon, as a key step toward conducting human activities on Mars.

The first mission defined within the RLEP is the Lunar Reconnaissance Orbiter (LRO). This mission is to fly to lunar orbit before the end of 2008. The second project, still under definition, is ideally to be flown by the end of 2009. Subsequent missions will be developed in conjunction with and in response to requirements still being formulated by the Exploration Systems Mission Directorate (ESMD) at NASA Headquarters, in concert with inputs from the Science Mission Directorate.

In order to keep pace with the evolving nature of the Exploration Program, a mixed mode of flight missions is envisioned for the RLEP. While LRO is planned for a Delta-class launch vehicle and its associated performance capabilities, this is not necessarily the case for all the follow-on flight missions. Follow-on missions may include landers, both soft and hard, utilizing impactors and surface probes, and possibly systems with limited surface and sub-surface mobility, as well as robotic sample/experiment "return" missions. Other missions may include communications, ranging, and navigation satellites, as well as lunar surface and Earth ground assets that help achieve these capabilities. Also under consideration are small sub-satellites that could better define the gravitational field of the Moon, particularly on the far side. Some flight missions may be launched on a smaller Expendable Launch Vehicle (ELV) if their total mass is less than 400 kg. Such missions may support options for smaller probes, impactors, bio-sentinels, sub-satellites, and other technology demonstrators.

Larger scale missions (i.e. Discovery-class or larger) may support risk mitigation or infrastructure requirements originating from other elements of the Exploration Vision. Some infrastructure may be developed externally to the RLEP program as a directed payload. The Exploration Program can utilize the quick response and relatively low cost of the RLEP to mitigate developmental risk on key manned flight system functions, such as automated rendezvous and docking, precision landing, or engine performance and control.

RLEP is unique in that as a program of multiple mission classes it can provide flexibility in both capability and response time that can be tailored to the individual Exploration Vision needs, be they for specific measurements, technology demonstration/maturation efforts, or infrastructure emplacement. It is a program that will constantly be evolving, and unquestionably have a broad range of content. RLEP is intended to be an adaptable enabler of human exploration of the Moon and beyond.

III. Program Objectives

The President's Vision for U.S. Space Exploration laid out the following objectives relative to "Space Exploration Beyond Low Earth Orbit," and specifically to the lunar program:

- Undertake lunar exploration activities to enable sustained human and robotic exploration of Mars and more distant destinations in the solar system.
- Starting no later than 2008, initiate a series of robotic missions to the Moon to prepare for and support future human exploration activities.
- Conduct the first extended human expedition to the lunar surface as early as 2015, but no later than 2020.
- Use lunar exploration activities to further science and to develop and test new approaches, technologies and systems, including use of lunar and other space resources, ultimately to enable sustained human and robotic exploration of Mars as well as more distant destinations in the solar system.

From these, the Exploration Strategy-to-Task-to-Technology (STT) process identified five primary objective themes for the RLEP program. These objectives are:

A. Preparing for Safe Landing and Selecting Exploration-relevant Sites

Any human-based extended-duration mission to the surface of the Moon will require (for navigation purposes) knowledge of global geodetic topography and detailed hazard-scale mapping for site selection and safe landing. Key environmental characteristics must be understood for risk reduction to human missions as well as robotic and human vehicle design. The radiation, thermal, and lighting environments are items of primary interest in preparation for a short stay on the Moon. Lunar polar regions are of particular interest for mapping and environmental characterization since there is the potential for locating water ice resources. As precursor robotic missions prepare for potentially longer duration human missions to other sites on the lunar surface, additional topographic and resource-relevant mapping will be required for site selection and landing safety.

B. Emplacing Infrastructure Support

Providing support for the human missions with preparatory and/or coincident placement of communications/navigation, power, and other necessary infrastructure is also a fundamental objective of the precursors. If it is eventually determined that humans must stay for a long time on the surface of the Moon to enable future human exploration of Mars, it is possible that infrastructure for resource extraction and generation would also be required.

C. Preparing for and Assessing the Possibility of Resource Utilization

Currently, the in situ resource of most interest is the potential for substantial deposits of water ice in the lunar polar regions. Lunar robotic precursors will acquire both orbital and *in-situ* ground truth data to determine whether the putative water ice actually exists, its accessibility, and abundance. If found, technology demonstrations would be required to validate techniques for energy-efficient extraction of water ice from the lunar surface materials. Oxygen in the lunar regolith and surface rocks is also of interest and robotic missions may undertake technology demonstrations for small-scale extraction of O_2. Additional surveying for resources and resource extraction (such as drilling) may be undertaken as part of the human missions. Longer duration stays on the surface will possibly lead to requirements for larger scale resource extraction and processing if it is determined that this is beneficial on the basis of cost/benefit analysis.

D. Maturing Technologies

Through the STT process, a set of critical technologies can be prioritized for investment and when available, can be demonstrated as part of the lunar robotic precursor program. Early technology demonstrations in RLEP include radiation and micrometeorite shielding assessment of materials with low mass atomic constituents that may be used for future missions. Critical components of human environmental monitoring systems can also be tested as a greater understanding of the lunar environment is acquired. It is expected that precision-landing technologies will be required for safe landings of the precursor robotic missions in the desired locations. Additional technology demonstrations such as dust mitigation will aid in Extravehicular Activity (EVA) suit design for humans and demonstration of thermal systems will aid in vehicle design for extreme thermal environments.

E. Preparing for Human-based *In-Situ* Science Activities

Supporting the highest priority research to be performed by the human missions on the Moon will involve cooperative work between humans and robots during the landed missions to perform key research activities such as life science experiments, highly informed sample selections (including subsurface), and other detailed investigations of the surface and interior of the Moon.

IV. Program Architecture

The RLEP architecture is being crafted to be responsive to the evolving needs of Exploration. It is intended to address key questions faced in the development of the Exploration missions and their necessary systems as framed in the five primary objective themes. As the questions change on the basis of discoveries and new capabilities, so will the solutions. Consequently, the RLEP architecture development is, and will continue to be, highly iterative in its implementation, preserving an option-based template at each step. Like the NASA Mars Exploration Program, which has been designed to be responsive to discoveries, the RLEP is designed to be responsive to the evolution of Exploration needs. We recognize that the specific character of Exploration needs will progress through the five broadly defined objectives previously outlined, but those needs best served by robotics beyond LRO are not yet clear. As a result, the RLEP is working with the leaders of Exploration to articulate the critical questions that must be addressed, with the corresponding time relevant reference frame, and then developing candidate strawman mission profiles that could be used to address these issues. This process is being used to define the potential pathways that RLEP may take in its future missions. Key to this activity is recognition that LRO will generate specific testable hypotheses that must be addressed either via follow-on orbital remote sensing missions or via a variety of surface-based missions. Programmatic constraints as well as solid systems-engineering practices will dictate the directions to be taken, as pathways are developed. Not knowing the actual mission requirements at this time, the RLEP Future Missions Office has focused on identifying elements that are common to all lunar missions, staring with the transportation options from Earth to the Moon.

Four primary approaches are possible for transport to the Moon. Direct lunar injection is the simplest, most proven approach to get to the Moon. This approach takes 4 – 4 ½ days to complete the transfer, and passes the spacecraft through the Earth's radiation belt only once. While it may not deliver the highest mass, it is the lowest risk. An approach using lunar phasing loops allows for a higher mass to be delivered for a given launch vehicle. The trade-offs are that it takes 2-3 weeks to complete the transfer, makes multiple passes through the Earth's belts, and adds some operational complexity. A weak stability transfer affords very modest gains in mass at the expense of mission complexity and extreme targeting precision. This approach only passes the spacecraft through the radiation belts once, but takes 90-100 days to complete the transfer. An electric propulsion spiral transfer approach has the greatest mass delivery potential for a given launch vehicle, although a sizeable amount of the additional mass is consumed by the 10kW+ power system needed to power the electric propulsion system hardware. This approach takes 2-3 years to complete the transfer and spends several weeks in the Earth's radiation belts. The spacecraft design is somewhat altered from a lunar optimized configuration so as to support the needs of the extended transit phase.

A range of delivery systems can be used for delivering the payload to the moon. These delivery systems, or mother ships, can be defined in four different categories. The (M-1) mother ship is the simplest delivery system, and does not stay in lunar orbit. The (M-1) mother ship assumes solids for capture and de-orbit. It requires the descent stage to perform the mid-course transit propulsive corrections, and provides its own communications back to Earth. If the entire mission mass were to go to the surface, then there would be no need for the (M-1) mother ship. The (M-2) and (M-3) mother ships achieve orbit and have increasing degrees and durations of support services for their descent packages. The most noteworthy distinction is that a (M-2) mother ship is designed to be launched into short-lived, full sun lunar orbits which will rapidly decay after orbit eclipses begin. This may occur within several days of launch. By comparison, the (M-3) mother ships are configured to survive 6 months or more, tolerating orbit eclipses. Both the (M-2) and (M-3) have an onboard propulsion system for mid-course correction and capture. (M-4) mother ships are advanced 3-axis stabilized platforms with high gain antennas and large data volume store and forward capabilities. The LRO mission is an example of a (M-4) class mother ship, where the payload was chosen to stay on the mother ship, in lunar orbit, instead of separating and descending to the surface.

Landing approaches were classified into three different categories; Soft, Rough (medium), and Hard. Hard landers are the least complicated of landers. They use their energy from orbit to penetrate the lunar surface. This can be useful to probes that are trying to sample below the surface, removing the need for the complexities of drilling. Some examples would be subsurface in-situ resource interrogation, subsurface thermal measurements, permittivity experiments, and radiation penetration tests. Alternatively, a hard lander could be used to deliver a simple payload to the surface if the lander were to be configured as crushable, kinetic energy absorbing media. Hard landers are envisioned using solids for de-orbit, but require a spin axis control system (non-solid) to properly reorient the vehicles to the surface before contact. These systems draw heritage from the Ranger Impact Capsule, DS-2 Microprobe, and military systems. Rough (or medium) landers use an airbag, or other crushable material, approach to make the final surface contact. These systems are good for maximizing payload mass when precision landing is not required or for landing on rugged or unknown surfaces. Rough landers do require some mass penalties to increase durability. Rough Landers are envisioned to use solids for de-orbit and descent; canceling horizontal velocity and then freefalling to the surface. Soft landers are the most complex, and therefore capable of precision landing. A high degree of payload integration is desirable for these systems in order to achieve maximum use of the reduced mass available to instrumentation by using systems for the dual purposes of lander and payload. Soft landers are envisioned as having throttleable propulsion systems and landing with shock absorbing legs. These landers would need to land in relatively smooth topography, unless advanced obstacle avoidance systems are incorporated. Soft landers have heritage in Surveyor, Viking, and numerous conceptual designs.

This mix of transportation, mother ships, and landers defines the generic capability that can be used to support a wide range of payloads with varying sizes, masses, requirements, schedules, costs, and procurement strategies. Many elements and techniques are common to all. This range of capabilities is definable enough that deliverable payload masses can be estimated. Table 1 outlines the payload capacity inherent to each approach. These boundary conditions are being used to guide RLEP architecture development.

V. Program Guidance

The RLEP is reaching out to the external community for input. Broadly scoped Requests for Information (RFI's) have already been issued by the program office. These requests solicited input for use in shaping program strategies. Thankfully, industry and academia eagerly responded with thoughtful ideas that have been helpful in shaping the program.

Additionally, an external advisory group has been formed to periodically address topics critical to the formation of the program plan. This group, the Lunar Exploration Advisory Group (LEAG), is first tackling the broad question of defining candidate scenarios for the early manned missions, and in doing so, helping to better characterize the gaps in current knowledge and capability that must be closed. These gaps will then be addressed by the evolved RLEP architecture.

VI. Implementation Strategy

The RLEP plans to have between one-half and two-thirds of the activities within its work content open to competition. A broad range of procurement approaches is anticipated to optimally address the large range of potential mission content. Broadly announced competitive procurements and partnerships will be used to the greatest extent possible. Participation by universities, industry, other government agencies, and small, disadvantaged businesses will be promoted and encourages in all procurements.

NASA Headquarters will procure scientific investigations through the Announcement of Opportunity (AO) process, managed with support from the RLEP Program Office. Headquarters will issue an AO to solicit payloads for a mission prior to the start of mission formulation. The announcement of the awards from the peer-reviewed proposals coincides with the start of the mission formulation.

VII. Lunar Reconnaissance Orbiter (LRO)

LRO is the first of the RLEP missions to the moon. The four primary measurement objectives of the LRO mission were defined by the Orbiter Requirements Definition Team (ORDT), approved jointly by the Associate Administrators for Exploration Systems, Space Science, Biological and Physical Research, and Space Flight on May 24, 2004. These objectives are summarized below:

1) Characterization of the lunar radiation environment, biological impacts, and potential mitigation. Key aspects of this objective include determining the global radiation environment, investigating the capabilities of potential shielding materials, and validating deep space radiation prototype hardware and software.
2) Develop a high resolution global, three dimensional geodetic grid of the Moon and provide the topography necessary for selecting future landing sites.
3) Assess in detail the resources and environments of the Moon's polar regions.
4) High spatial resolution assessment of the Moon's surface addressing elemental composition, mineralogy, and Regolith characteristics.

Through an Announcement of Opportunity for the LRO, NASA selected six proposals to provide instrumentation and associated exploration/science measurement investigations for the LRO. These measurements will characterize future robotic and human landing sites. It also will identify potential lunar resources and document aspects of the lunar radiation environment relevant to human biological responses. The measurements are critical to the key decisions that must be made before the end of this decade for the Exploration Systems Mission Directorate. The six selected investigations and principal investigators are:

Lunar Orbiter Laser Altimeter (LOLA) Measurement Investigation – principal investigator Dr. David E. Smith, NASA Goddard Space Flight Center (GSFC), Greenbelt, MD. LOLA will determine the global topography of the lunar surface at high resolution, measure landing site slopes and search for polar ices in shadowed regions.

Lunar Reconnaissance Orbiter Camera (LROC) – principal investigator Dr. Mark Robinson, Northwestern University, Evanston, IL. LROC will acquire targeted images of the lunar surface capable of resolving small-scale features that could be landing site hazards, as well as wide-angle images at multiple wavelengths of the lunar poles to document changing illumination conditions and potential resources.

Lunar Exploration Neutron Detector (LEND) – principal investigator Dr. Igor Mitrofanov, Institute for Space Research, and Federal Space Agency, Moscow, Russia. LEND will map the flux of neutrons from the lunar surface to search for evidence of water ice and provide measurements of the space radiation environment which can be useful for future human exploration.

Diviner Lunar Radiometer Experiment – principal investigator Professor David Paige, UCLA, Los Angeles, CA. Diviner will map the temperature of the entire lunar surface at 300 meter horizontal scales to identify cold-traps and potential ice deposits.

Lyman-Alpha Mapping Project (LAMP) – principal investigator Dr. Alan Stern, Southwest Research Institute, Boulder, CO. LAMP will observe the entire lunar surface in the far ultraviolet. LAMP will search for surface ices and frosts in the polar regions and provide images of permanently shadowed regions illuminated only by starlight.

Cosmic Ray Telescope for the Effects of Radiation (CRaTER) – principal investigator Professor Harlan Spence, Boston University, Boston, MA. CRaTER will investigate the effect of galactic cosmic rays on tissue-equivalent plastics as a constraint on models of biological response to background space radiation.

LRO is a one year duration reconnaissance mission to be flown in a low (50 km) lunar polar orbit. It will be launched on a Delta II class launch vehicle in late 2008 and fly a direct insertion trajectory to the moon. The observatory is a 3-axis stabilized nadir pointing platform with a total mass, including fuel, of approximately 1000 kg. The preliminary design for the LRO orbiter is shown in Fig. 2 and key attributes of the spacecraft are given in Table 2.

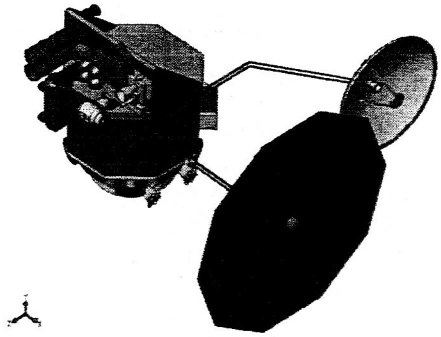

Figure 2. LRO Conceptual Design

LRO Flight Segment Mass & Power Estimates		
Range of on-going design trades		
Subsystem	**Mass (kg)**	**Orbit Average Power (W)**
Instrument Payload	100	100
Spacecraft Bus (Dry)	454 - 484	300 - 355
Propellant	396 - 583	
Total:	980 - 1137	400 - 455
Launch Vehicle Capability (C3 = -2.0)	1285 - 1485	

Table 2. Key Spacecraft Attributes

In addition to the one year primary mission, LRO is being designed to be potentially flow for up to four addition years in an extended mission. Possible objectives for an extended LRO mission include functioning as a communication rely asset for subsequent missions and performing additional target observations in support of exploration planning.

VIII. Other Missions

The NASA 1008 LRO Mission is both complementary and synergistic with the three international lunar orbiter missions planned for the 2006-2010 time interval. While LRO is optimized to be exploration-centric, focusing on measurement sets designed to inform critical decisions about how to cost-effectively send humans as explorers to the Moon, the international missions are more science-focused, with attention to basic characterization of the moon with imaging, elemental (i.e., compositional) mapping, and associated particles and fields measurements.

The most comprehensive of these is the Japanese JAXA Selene mission, with a payload consisting of a powerful suite of 13 sensor systems. Selene will observe the Moon as a science orbiter, and is highly complementary to the LRO mission, by potentially offering farside gravity field data, high resolution global multispectral data, 20km scale elemental mapping, and other interesting complementary datasets, including subsurface microwave sounding.

The India (ISRO) Chandrayaan-1 mission is another science orbiter, with strong synergies to NASA's LRO, and it may carry one or more US payload(s), including an S-band radar transponder as a technology demonstration for advanced, miniaturized telecommunications and 12cm wavelength SAR for ~100m scale surface roughness imaging and bistatic sounding. Chandrayaan-1 will map the global mineralogy of the Moon and other scientific aspects of the planet, thereby complementing the exploration focus of LRO.

The China lunar orbiter Chang'e could also complement the US LRO, as it will carry a large payload optimized basic scientific characterization, including compositional mapping and stereo imaging, as well as mapping of solar wind. All of the international orbiters will observe the Moon from orbits in the 100-200 km altitude range, while LRO will map the lunar surface from 35-50 km to provide the measurement sets required to enable human exploration.

This impressive array of international lunar science orbiters, when combined with data already being produced by ESA's SMART-1 lunar orbiter, and with that anticipated from LRO, will offer a new view of the Moon as a planet, and undoubtedly discover new aspects of this crustal evolution, volatile history, and state of interaction with the Sun. As such, LRO will largely serve to provide the high-resolution and 3D context for the datasets expected to come from the lunar missions by ESA, India, Japan, and China.

IX. Program Organization

The ESMD is the RLEP customer – providing the requirements and objectives that form the basis of the mission set. NASA's Science Mission Directorate, through the Solar System Exploration Division RLEP Program Director Tom Jason, is responsible for management of RLEP. The RLEP Program Office, managed by James Watzin at GSFC, is responsible for implementation. All missions (projects) of the RLEP will be managed by this office. In order to promote synergy and efficiency, the RLEP office provides shared business, administrative, and systems engineering services to all of the mission projects. Craig Tooley is the Project Manager for the LRO mission.

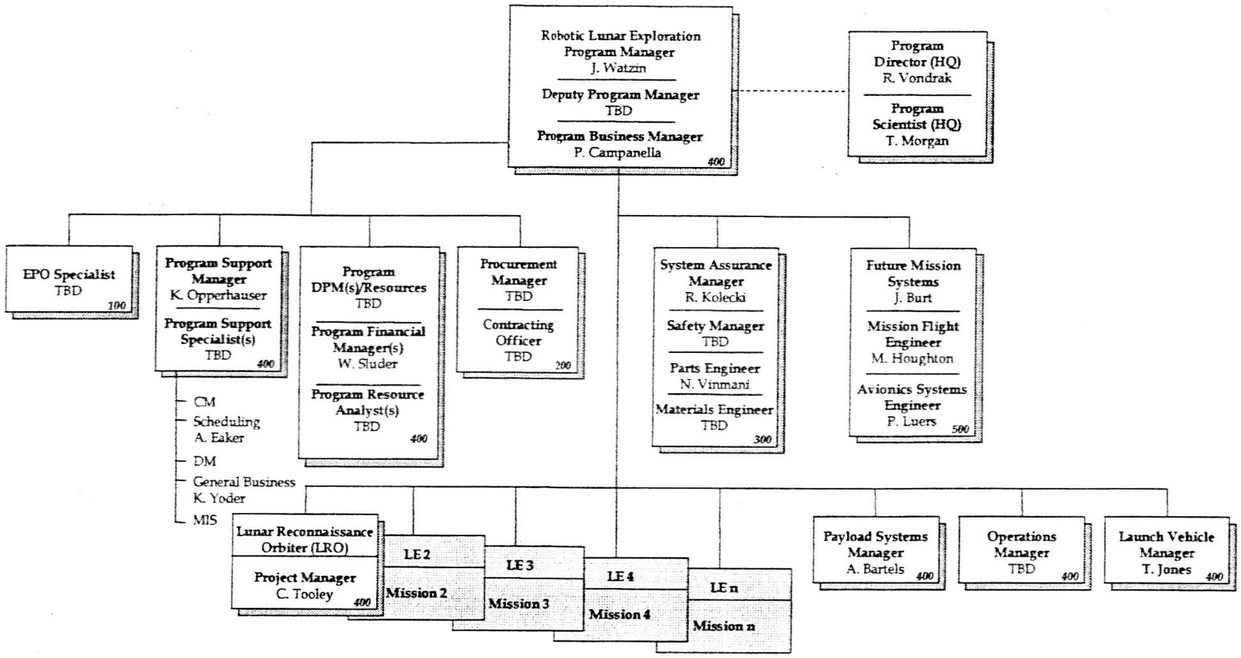

Figure 3. Robotic Lunar Exploration Program Organization Chart

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